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A Subharmonic Mixer Using a Planar Doped Barrier Diode with Symmetric Conductance

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Abstract—Planar doped barrier (PDB) diodes with symmetric I - V characteristics have been successfully used in a subharmonically-pumped coplanar stripline mixer circuit. A conversion loss around 6 dB has been measured using a 1.2 GHz local oscillator at a pump power of 7 dBm and a 2 GHz signal frequency for large area, 100 μ m diameter PDB mesa diodes. The particular advantages of this device structure are that a single PDB replaces two critically matched Schottky barrier diodes in conventionally balanced mixers, and the PDB's designable barrier height reduces the local oscillator power requirement.

INTRODUCTION

THE FIRST demonstration of a subharmonically-pumped mixer using an antiparallel conducting pair of Schottky barrier diodes was reported by Schneider and Snell [1]. The subharmonic mixer has a number of advantages in comparison to conventional mixers, especially at millimeter-wave frequencies. The local oscillator (LO) power requirement is easier to meet since the LO operates at an even submultiple (about one half) of the signal frequency. The separation of the LO and signal frequencies through bandpass filtering is also simplified due to the large difference in these frequencies. In addition, the symmetric I - V characteristic of the subharmonic mixer affords substantial AM noise suppression of the LO [2]. However, the performance of subharmonic mixers which utilize a pair of Schottky barrier diodes is critically dependent upon matching the electrical characteristics of the two diodes as well as their placement in the microwave circuit. Conductance or phase mismatches between the diodes at any of the mixing product frequencies leads to degraded conversion loss and noise figure in the mixer. A much more attractive alternative to the two-diode mixer is the use of a single diode element with a symmetrical I - V characteristic. Schottky barriers employing a reverse tunneling current and graded bandgap heterojunctions have been proposed to approximate this characteristic [3]. However, this article reports the use of a planar doped barrier (PDB) to obtain a truly symmetric I - V characteristic in a single diode. Additionally, the ability to design the barrier height and capacitance in the PDB diode makes it ideally suited for use in subharmonic mixers.

PDB DIODE THEORY

The planar doped barrier concept has been previously described [4, 5]. The PDB is a majority carrier device structure with an n^+ - i - p^+ - i - n^+ doping configuration in which an extremely thin, fully depleted acceptor layer (20-100 Å) is used to form a triangular potential profile of predetermined shape and height. For the particular case of a symmetric I - V curve

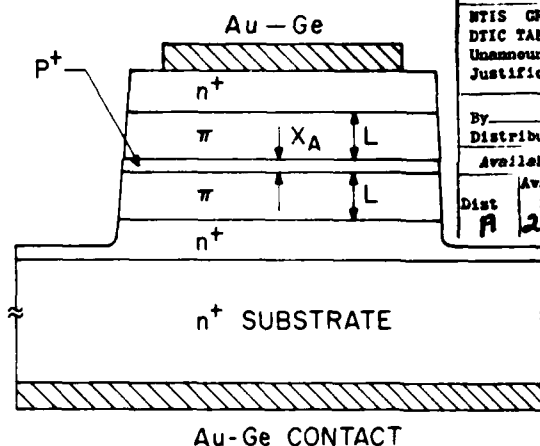


Fig. 1. Schematic cross-section of a GaAs PDB diode with a symmetric current-voltage characteristic (not drawn to scale).

for a subharmonic mixer, the acceptor layer is positioned in the middle of the undoped region and separated by the distance L from each of the respective donor regions (Fig. 1).

Assuming that the ionized impurity widths of the acceptor layer and at the edges of the donor layers are much less than L (typically < 100 Å), and the potential due to the ionized impurities in the undoped regions is negligible, then the zero-bias barrier height ϕ_{BO} is given approximately by

$$\phi_{BO} = \frac{qN_A X_A L}{2\epsilon} \quad (1)$$

where q is the unit electron charge, N_A the volume density, X_A the acceptor width, and ϵ is the dielectric permittivity of the semiconductor. The capacitance of the diode which is constant with applied voltage and is approximately equal to

$$C = \frac{\epsilon a}{2L} \quad (2)$$

where a is the diode area.

The symmetric I - V characteristic of the diode can be expressed by a hyperbolic sine function [3] of the applied voltage V , whereby

$$I = 2I_s \sinh\left(\frac{qV}{nkT}\right) \quad (3)$$

The saturation current I_s is related to the zero-bias barrier height by

$$I_s = aA^* T^2 \exp\left(\frac{-q\phi_{BO}}{kT}\right) \quad (4)$$

In (3) and (4), k is Boltzmann's constant, T the absolute temperature, and A^* the effective Richardson constant. The n -

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factor in (3) is determined by the geometry of the diode which effectively divides the applied voltage across the barrier region. Ideally, $n = 2$ for a truly symmetric PDB diode. The n -factor should not be confused with the so-called ideality factor which is an empirical parameter used to describe the effects of image force lowering and interface traps in Schottky barriers.

Schneider [3] has reported on the electrical properties of diodes exhibiting symmetric I - V characteristics for frequency conversion. An ac analysis was performed through a Taylor series expansion of the nonlinear current waveform. The key features derived from this analysis are: there is no dc current flowing through the junction, the device current contains only odd order harmonics of the pump frequency, and the conductance contains only even order harmonics of the pump frequency.

DIODE FABRICATION AND DC CHARACTERISTICS

GaAs planar doped barrier structures were grown by MBE in a Varian-360 system. Silicon and beryllium were used as n -type and p -type dopants, respectively, at levels of approximately 10^{18} cm^{-3} . The undoped regions were low 10^{14} cm^{-3} p -type, thus contributing negligible charge to the potential. Typical growth parameters were as follows: growth rate $r = 200 \text{ \AA/min}$, substrate temperature $T_s = 580^\circ\text{C}$, and flux ratio $\text{As}_4/\text{Ga} = 2$. Mesa diodes were formed by chemical etching and alloying of evaporated Au/Ge contacts to result in the structure shown in Fig. 1.

The parameters for PDB Diode 265 are the following: planar acceptor density $N_A X_A = 3.6 \times 10^{11} \text{ cm}^{-2}$, undoped region widths $L = 2000 \text{ \AA}$, and mesa diameter of $100 \text{ }\mu\text{m}$ ($a \approx 7.85 \times 10^{-5} \text{ cm}^2$). A photograph of the dc I - V curve for this diode is shown in Fig. 2. The excellent symmetry for the I - V curve was checked with a dc electrometer. Within experimental error, there was no measurable difference between the forward and reverse I - V characteristics.

A logarithmic plot for the current dependence upon applied voltage for PDB Diode 265 is shown in Fig. 3. The equations for determining the n -factor and zero-bias barrier height ϕ_{BO} are found by taking the natural log of (3) and (4).

$$\frac{d(\ln I)}{dV} = \frac{q}{nkT} \quad (5)$$

$$\phi_{BO} = \frac{-kT}{q} \ln \left(\frac{I_s}{aA^*T^2} \right) \quad (6)$$

Thus, n and ϕ_{BO} can be determined from the slope and intercept of the Log I - V curve. From the inset box in Fig. 3, there is seen to be excellent agreement between the theoretical and experimental calculations of these parameters. These results demonstrate that MBE provides the requisite control necessary to form PDB device structures.

SUBHARMONIC MIXER RESULTS

The symmetric PDB diodes were evaluated in a subharmonic mixer using a coplanar waveguide fixture fabricated on a $1'' \times 1'' \times 0.015''$ Al_2O_3 substrate. The ground planes and center conductor were formed by photolithography and Au evaporation. The diode wafer was sliced into $0.080''$ square chips and one diode on a chip was wire-bonded to the coplanar waveguide. A photograph of the resultant test fixture for the subharmonic

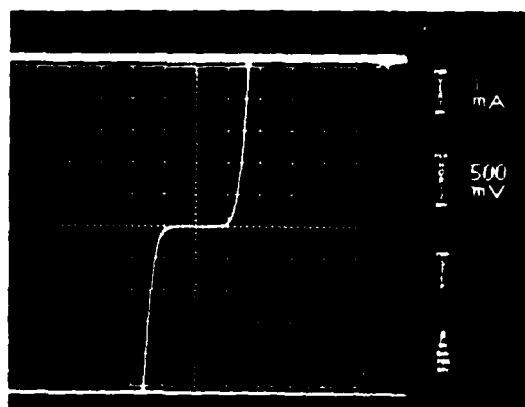


Fig. 2. Current-voltage characteristic of PDB Diode 265 with the following diode parameters: $N_A X_A = 3.6 \times 10^{11} \text{ cm}^{-2}$, $L = 2000 \text{ \AA}$, area = $7.85 \times 10^{-5} \text{ cm}^2$.

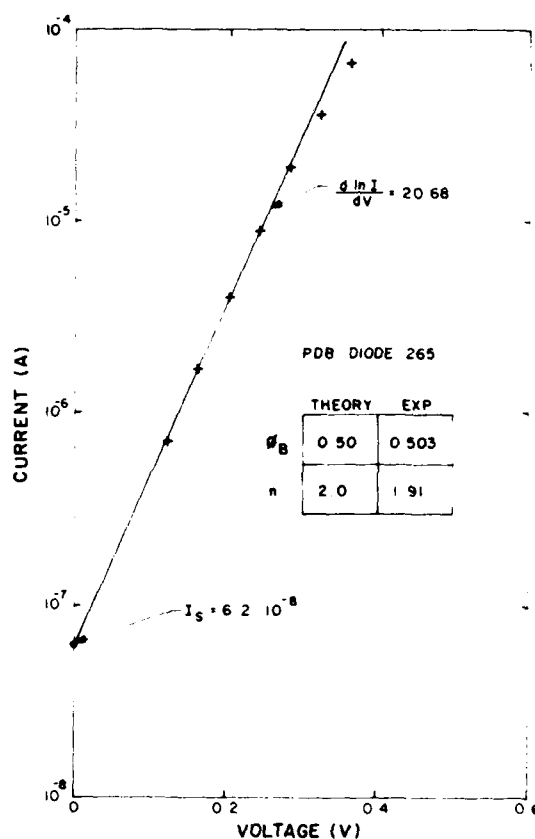


Fig. 3. Log current-voltage characteristic of PDB Diode 265. The slope and intercept are used in determining the diode n -factor and barrier height, respectively.

mixer is seen in Fig. 4. A series resistance of $R_s = 7 \text{ ohms}$ and capacitance of $C = 1.8 \text{ pF}$ was measured for PDB Diode 265. This corresponds to a cut-off frequency of $f_c = 12.6 \text{ GHz}$ which, therefore, restricted RF measurements to a few GHz. The high value of the capacitance was due to the large area of these diodes. The results reported here serve to demonstrate the potential use of symmetric PDB diodes in subharmonic

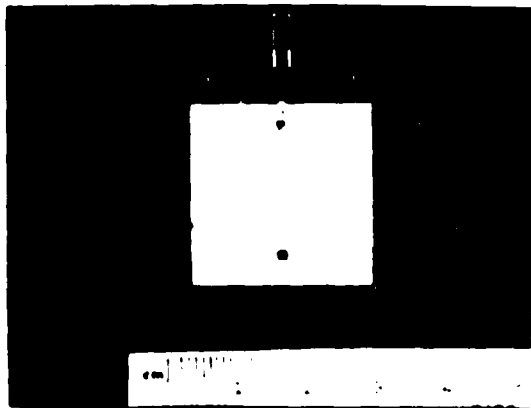


Fig. 4. Photograph of subharmonic mixer test fixture.

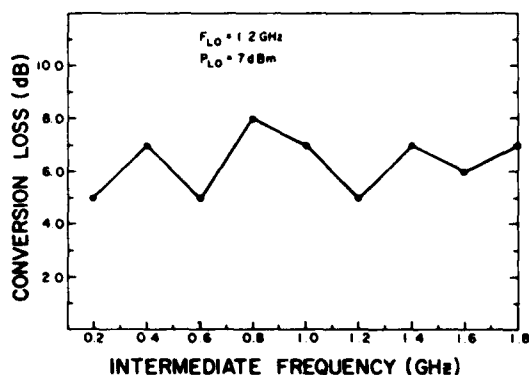


Fig. 5. Conversion loss as a function of the intermediate frequency with fixed local oscillator of 1.2 GHz and pump power of 7 dBm.

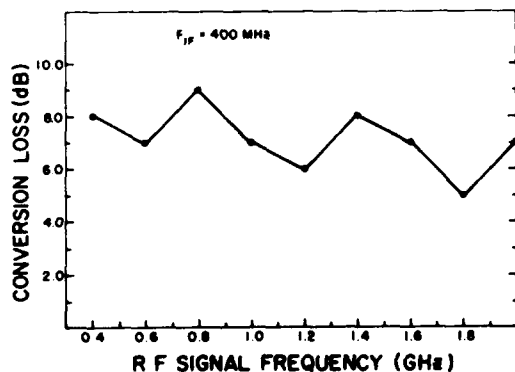


Fig. 6. Conversion loss as a function of the RF signal frequency with fixed intermediate frequency of 400 MHz.

mixers. High cut-off frequency ($f_c > 1000 \text{ GHz}$) PDB diodes can easily be obtained by reducing the diode area and optimizing the ohmic contact metallization. The performance of a millimeter wave PDB subharmonic mixer will be reported in a subsequent publication.

Using separate signal generators as the local oscillator and signal source, the conversion loss was measured as a function

of several different parameters. Figure 5 shows the dependence of the conversion loss upon the intermediate frequency (IF). The conversion loss varies from 5.0 to 8.0 dB over an IF range of 0.2 to 1.8 GHz. It should be noted that this conversion loss is achieved at a pump power of only 7 dBm for the LO, which is about a factor of one half the required pump power for GaAs Schottky barrier diode mixers. This demonstrates that a substantial reduction in the LO power can be achieved with the designable barrier height in the PDB. Diode 265 had a barrier height of 0.5 V, so that a further decrease in the barrier height should lead to an even lower required pump power for the mixer. Figure 6 shows the variation of the conversion loss as a function of the RF signal frequency with a fixed $IF = 400 \text{ MHz}$. The conversion loss varies between 5.0 and 9.0 dB over a RF signal frequency range of 0.4 to 2.0 GHz. The conversion loss is relatively flat with a maximum deviation of 4.0 dB over this entire frequency range. Pumping of the mixer diode has also been achieved at submultiples of less than one half the signal frequency without a significant degradation of the conversion loss. This possibility is attractive for use in very-high-frequency mixers.

These preliminary results clearly demonstrate the potential use of PDB diodes in subharmonic and conventional mixer circuits. Work is presently under way in the development of PDB diodes for microwave and millimeter-wave mixers.

CONCLUSION

A novel subharmonic mixer has been demonstrated which uses a PDB diode with a symmetric I - V characteristic. A minimum conversion loss of 5 dB has been obtained for a RF signal of around 2 GHz and a local oscillator at 1.2 GHz with a pump power of 7 dBm. In this configuration, a single PDB diode replaces two well-matched Schottky barrier diodes in conventional balanced mixers and the designable barrier height of the PDB reduces the local oscillator power requirement. These results are presently being applied in the design of very high frequency millimeter-wave subharmonic mixers.

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